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A STUDY ON THE SPEED CONTROL OF A BLAC MOTOR BY BACK-EMF FEEDFORWARD COMPENSATION

DONGHOON BAN, JAESEUNG HONG, SUNGHO JIN & SEONGHUN LEE

Convergence Research Center for Future Automotive Technology, Dgist, Korea

ABSTRACT

A PI controller is used to control the speed of a motor, but the gain of the PI controller is limited according to the system. Thus, the PI controller alone cannot meet the control performance requirements of the motor. A method involving back-electromotive force (back-EMF) compensation can solve this problem. Here, a feedforward compensation method based on the speed is used to compensate for the back-EMF. However, it is difficult to measure speed in the extremely low speed range, so it is difficult to compensate the back-EMF. In addition, the rate of the back-EMF compensation is modified by adjusting the gain. This proposed method of the back-EMF compensation is proven by simulation and experiment. The root mean square (RMS) value for the speed error is measured when the back-EMF is compensated for, when the back-EMF is not compensated for and when the gain of the back-EMF compensation is adjusted. The study confirms that the proposed algorithm is superior in the RMS value of the speed error.

KEYWORDS: BLAC, Back-EMF, Vector Control, Feed Forward Compensation & PI Controller

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Original Article

INTRODUCTION

BLAC motors are widely used in the industry because they make little noise, electrically and mechanically, and they have the advantage of big power and low inertia. Generally, sinusoidal control is used to operate a BLAC motor, and the PI controller is used to control the speed. The PI controller is a simple control algorithm and has excellent driving characteristics, but the gain of the PI controller is needed to ensure the stability of the system. Therefore, the performance cannot be ensured by only the PI controller at high speed. Various feedforward compensation methods have been suggested to solve these problems.

In [1], the back-EMF wave form was studied in order to minimize the torque ripple by modifying the shape of the rotor and stator. In [2], a new flux switching permanent magnet machine was proposed. It is expected to have a bright future in a wide variety of drive applications with the requirements of high reliability and high power density. In [3], harmonics of back-EMF was compensated for in order to reduce the current ripple of the PMSM. In order to reduce the influence of a non0ideal permanent magnet state, a harmonic back-EMF compensation strategy was proposed. Rotor flux linkage estimation and compensation is a reasonable solution for better motor operation [4-5]. In [6], the authors used a sinusoidal back-EMF waveform in order to minimize the torque ripple when the BLAC motor was operating. In [7], the researchers studied the reasons for harmonic generation with a six-leg and three-phase inverter for a PMSM. When the windings of each phase are independent, a zero-sequence harmonic appears in both the back-EMF and currents. It makes torque ripple, generating noise and vibration when the motor is running. Generally, the back-EMF is studied to reduce the torque ripple and to precisely control the speed.

The back-EMF feedforward compensation method is used to control the speed of the BLAC motor. However, the estimated back-EMF is incorrect when the speed is very low or the fluctuation of the speed is severe. The back-EMF estimated inaccurately adversely affects the speed control of the motor, so the rate of the back-EMF compensation is controlled by adjusting the gain of the estimated back-EMF according to the speed. We conducted a study to accurately compensate for the back-EMF. The RMS value of the speed error was measured and compared in an experiment and in a simulation when the back-EMF is compensated for, when it is not compensated for and when the rate of the estimated back-EMF is adjusted.

BLAC MOTOR CONTROL

The equivalent circuit of the three-phase BLAC motor and PWM inverter are presented in Figure 1. Equation (1) is the voltage equation of the BLAC motor for each phase. It consists of the resister, the inductor and the back-EMF.

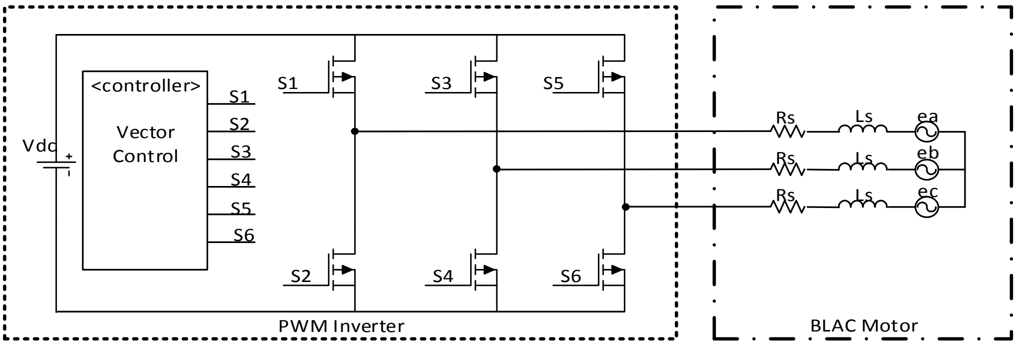


Figure 1: The Equivalent Circuit of the Three-Phase BLAC Motor and Inverter

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where V_a, V_b and $V_c$are the phase voltage of each phase, i_a, i_b and i_c are the phase current of each phase,R_s is the resister of each phase, $L_s$is the inductance of each phase, and e_a, e_b, e_c are the back-EMF of each phase.

The current of each phase is expressed by the direct component of the d-q axis on the stationary frame. And the back-EMF of the BLAC motor acts as a disturbance on the current control system. Therefore, the controlled direct current component exerts a bad influence. Generally, the back-EMF is expressed as a function of the speed, which is different depending on the motor. It is also expressed differently depending on the frame to control the current. The components of the back-EMF are the speed, the inductance, the current and the magnetic flux. Equations (2) and (3) are the d-q axis voltage equation on the stationary frame.

$$v_{ds}^r = R_s i_{ds}^r + L_s \frac{di_{ds}^r}{dt} - \omega_r L_s i_{qs}^r \quad (2)$$

$$v_{qs}^r = R_s i_{qs}^r + L_s \frac{di_{qs}^r}{dt} - \omega_r (L_s i_{ds}^r + \emptyset_f) \quad (3)$$

where v_{ds}^r and v_{qs}^r are the voltage on the d-q axis on the stationary frame, L_s is an inductor, ω_r is the speed and $\emptyset_f$ is the magnetic flux.

The variation of the back-EMF is small due to the large inertia of the motor, but the response of the current controller is late. Then the effect of the back-EMF can be ignored. On the other hand, the effect of the back-EMF cannot be

ignored due to the small inertia of the motor on the system which requires a fast response such as a servo system. It is difficult to get a good performance due to the influence of the interference component of the back-EMF even if the closed loop control of the current is controlled. In particular, in case of high speed, the performance of the current control is affected badly because the back-EMF is large. Thus, significant fluctuations of the current occur due to the back-EMF in the high speed range. An effective way to suppress the influence of the back-EMF is to estimate the back-EMF and to compensate for the back-EMF, which is regarded as the disturbance. The compensation for the back-EMF on the current control system of the motor is presented in Figure 2. The back-EMF as a disturbance is performed and is compensated for as much as the generated back-EMF. It is easy to control because it simplifies the linear system when the generated back-EMF performs the feed forward compensation.

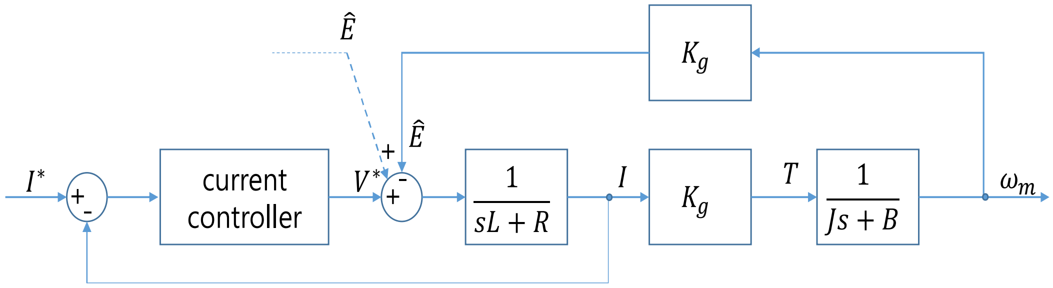


Figure 2: The Compensation of the Back-EMF on the Current Control System

The feed forward compensation value of the back-EMF is added to compensate for the back-EMF in the d-q voltage reference which is the output of the PI current controller. Equation (4) is the voltage reference given in the inverter. Equation (5) is the component of the back-EMF for d-q axis.

$$V_{ds}^e = V_{ds\_fb}^e + V_{ds\_ff}^e, V_{qs}^e = V_{qs\_fb}^e + V_{qs\_ff}^e \quad (4)$$

$$V_{ds\_ff}^e = -\omega_r L_{qs} i_{qs}^r, V_{qs\_ff}^e = \omega_r \left(L_s i_{ds}^r + \emptyset_f\right) \quad (5)$$

where V_{ds}^e and $V_{qs}^e$are the voltage references of the d-q axis, $V_{ds\_fb}^e$ and $V_{qs_fb}^e$are the outputs of the PI controller on the d-q axis, and $V_{ds\_ff}^e$ and $V_{qs_ff}^e$are the components of the back-EMF on the d-q axis.

The correct value of the magnetic flux, inductance, current and speed are needed to make an accurate estimate of the back-EMF, but the magnetic flux and the inductance are defined when the motor is designed, and the current value is measured in each phase. The speed is measured through the encoder sensor. The fluctuation of the speed is severe when the speed is very low. So the back-EMF is not calculated exactly because the low speed is not measured exactly

BACK-EMF COMPENSATION

Generally, the moving average is used to measure the speed. It uses the most recent data of the average speed. It is easy to remove the noise and has a good response for the speed. Equation (6) is the moving average equation for the speed.

$$\bar{v}_k = \bar{v}_{k-1} + \frac{v_k - \bar{v}_{k-n}}{n} \quad (6)$$

where$\bar{v}_k$ is the average speed, v_k is the current speed and $n$is the number of the measured data.

The back-EMF needs to be measured exactly for the feedforward compensation of the back-EMF. It is difficult to estimate the speed exactly when the speed is very low or the fluctuation of the speed is severe, so the dead zone is defined

in the low speed range and the less back-EMF is reflected. When the back-EMF is not reliable, less back-EMF is reflected. When the reliability of the back-EMF is ensured, the total back-EMF is reflected. The rate of the back-EMF compensation depending on the RPM is presented in Figure 3. The dead zone is from 0 to 500 RPM to ignore the effect of the back-EMF. Equation (7) is the gain for the back-EMF.

$$\text{Gain}(\%) = \frac{1}{5}(RPM - 500), \text{Gain} \geq 0, RPM \ \geq 500 \quad (7)$$

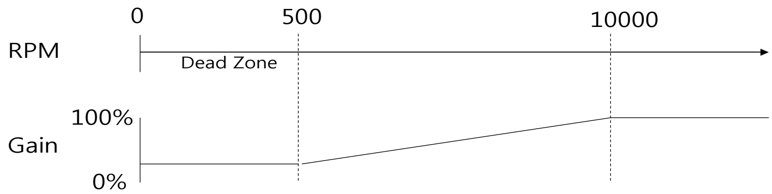


Figure 3: The Rate of the Back-EMF Compensation Depending on the RPM and Dead Zone

EXPERIMENTAL RESULTS

The system structure is shown in Figure 4. The vector control method is calculated to operate the current control using the output of the speed controller. The back-EMF, which is calculated using the speed, is reflected to the vector control. The voltage reference, which does the feed forward compensation of the back-EMF, operates the inverter, and the inverter operates the motor. The speed is calculated using the encoder sensor. The back-EMF is estimated and the speed controller is operated by the measured speed.

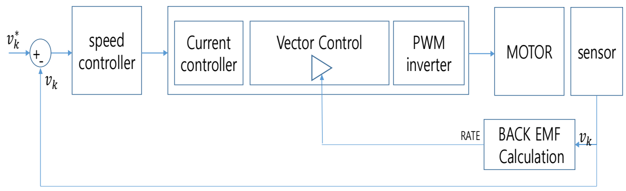


Figure 4: The System Structure

Simulation

A simulation is performed to verify the proposed algorithm. The simulation structure is shown in Figure 5. The simulation is composed of the inverter part, the load part, the motor part, the monitoring part, and the controller part. The result of the simulation is shown in Table 1. and Figure 6.

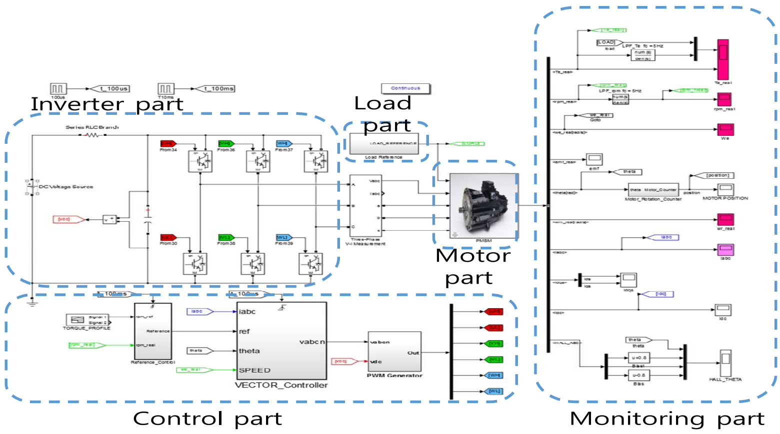
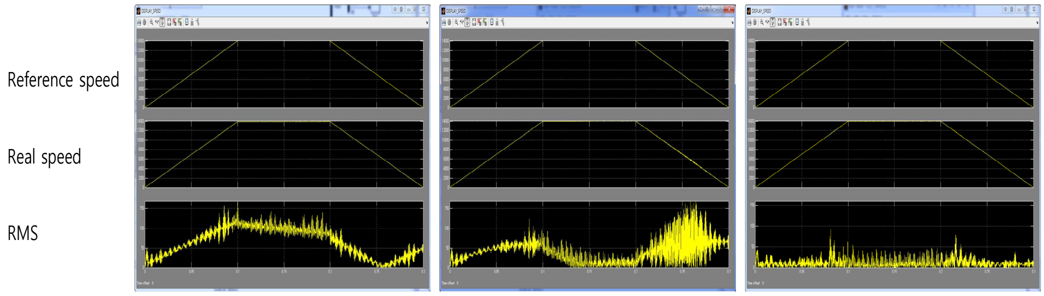


Figure 5: The Simulation Structure

Table 1: The Result of the Simulation

	RMS Value (Reference Speed – Real Speed)		
0 → 14000 → 0	No compensation	Compensation(speed)	Compensation(rate)
	76.03	50.55	15.21



(a) (b) (c)

Figure 6: The Simulation Result (A) No Compensation of the Back-EMF (B) Compensation of the Back-EMF (Speed) (C) Compensation of the Back-EMF (Rate)

Experimental Results

The response time and the RMS value are measured to verity the performance of the proposed algorithm when the back-EMF is compensated for, is not compensated for and is compensated for according to the proposed algorithm. The parameter of the motor is shown in Table 2. The system picture is shown in Figure 7. The RMS value is the difference between the reference speed and the real speed. The error of the speed decreased significantly with the proposed method. The RMS value of the speed error are shown in Table 3. and Figure 8.

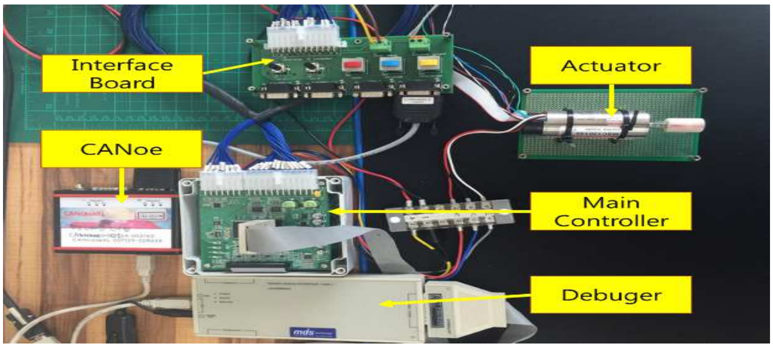


Figure 7: The Real System

Table 2: The Specification of the Motor

Task	Description	Task	Description
Rs	0.386Ω	Torque Constant	0.0276Nm/A
Ld	0.0653mH	Magnetic flux	0.0092V.S
Lq	0.0653mH	Rotor Inertia	0.00000333kgm^2

Table 3: The RMS Value of the Speed Error

	RMS Value(Reference Speed – Real Speed)		
0 → 10000 → 0	No compensation	Compensation(speed)	Compensation(rate)
	270.1	200.3	179.4

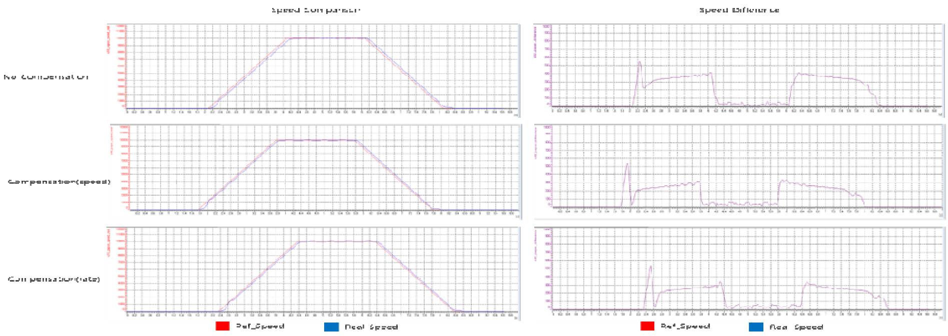


Figure 8: The Experimental Result (A) No Compensation of the Back-EMF (b) Compensation of the Back-EMF (Speed) (C) Compensation of the Back-EMF (Rate)

CONCLUSIONS

We conducted feed forward compensation of the back-EMF to increase the performance of a motor. It is very difficult to compensate for the back-EMF exactly when the speed is very low or the fluctuation of the speed is severe. Therefore, we adjusted the rate of the feed forward compensation to solve these problems. The dead zone where the feed forward compensation is not done was defined. We verified the proposed algorithm in which the rate of the feed forward compensation back-EMF was adjusted through a simulation. We further confirmed the performance of the proposed algorithm through the operation of a real motor, which confirmed that the proposed algorithm is superior in RMS value.

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